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Mining Induced Seismicity in the North Staffordshire Coalfield, England

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Mining induced seismicity associated with long-wall coal extraction in North Staffordshire, England, has been investigated in order to establish the cause and mechanism of the seismicity. The study shows that seismicity is directly caused by active mining with earth tremor hypocentres moving in unison and in advance of the face. The seismicity does not appear to be directly associated with any of the major faults bounding the mined area. The largest earth tremors have a local magnitude, M_L, of approximately 3, and of 711 earth tremors detected on a seismometer network situated in the coalfield, 54 events were sufficiently large to be felt by local residents. The majority of the larger earth tremors have a shear fracture source and are thought to be generated in strata overstressed as a consequence of the interaction of old coal workings with the active coal face. The remaining smaller tremors, which are not felt, have mostly an implosional source mechanism suggesting that they are generated by strata collapse.

1. INTRODUCTION

Small earth tremors associated with the mining of coal have occurred throughout the last century in North Staffordshire. On 15th July 1975, a large earth tremor was felt over an extensive area of Stoke-on-Trent. The earth tremor, of modified Mercalli scale intensity VI and local magnitude, M_L, of 2.8 (as estimated by the Institute of Geological Science Lownet seismometer network) was the climax of a swarm of tremors which had been felt in the area throughout early 1975 and continued to be felt until August 1977. Subsequent tremors never reached the intensity of the 15th July 1975, event but still caused concern to local residents. In response to the public concern created by the large earth tremor, a seismic study of the earth tremors was undertaken. The principal contributors to the investigations have been the Geology Department of Keele University, the Global Seismology Unit of the Institute of Geological Sciences, and the Mining Research and Development Establishment of the N.C.B. The objective of the investigation was to establish the cause and mechanism of the tremors which were suspected of being associated with the extensive coal mining activity which occurs under Stoke-on-Trent, a conurbation of approximately 250,000 population.

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The area which experienced the seismic activity is situated in the South of Stoke-on-Trent in the vicinity of Hanford and Trent Vale. Between 1973 and 1977 the area was mined for coal in the Ten Feet seam at a depth of approximately 900 m below the surface. The location of the panels numbered 202–206 are shown in Fig. 1.

The technique used for the mining of panels 202–206 in the Ten Feet seam was that of longwall extraction with total caving. With this method a machine removes a web of coal about 0.45–0.55 m deep off a face about 150–200 m long in one pass. The height of extraction was approximately the thickness of the seam (2.4 m) but up to 0.6 m of coal may be left to form a roof and up to 0.3 m left to form a floor if the adjacent rock is very friable or weak. The rate of progress of the face was usually between 12 and 24 m per week. Cutting took place on one, two or three shifts per day on weekdays but only rarely at weekends. In the longwall mining technique with total caving, the roof is supported for about 4–5 m behind the face by yielding hydraulic chocks. These are advanced either immediately the machine has passed (if it cuts in both directions) or after the machine has been 'flitted' back to the face-end (if it cuts in one direction only). After the supports have moved over, the roof behind them is free to fall and usually does so within a matter of minutes. Only a limited height (approximately equal to twice the height of extraction) falls and breaks up in the waste area. The upper beds settle onto this broken rock, recompressing

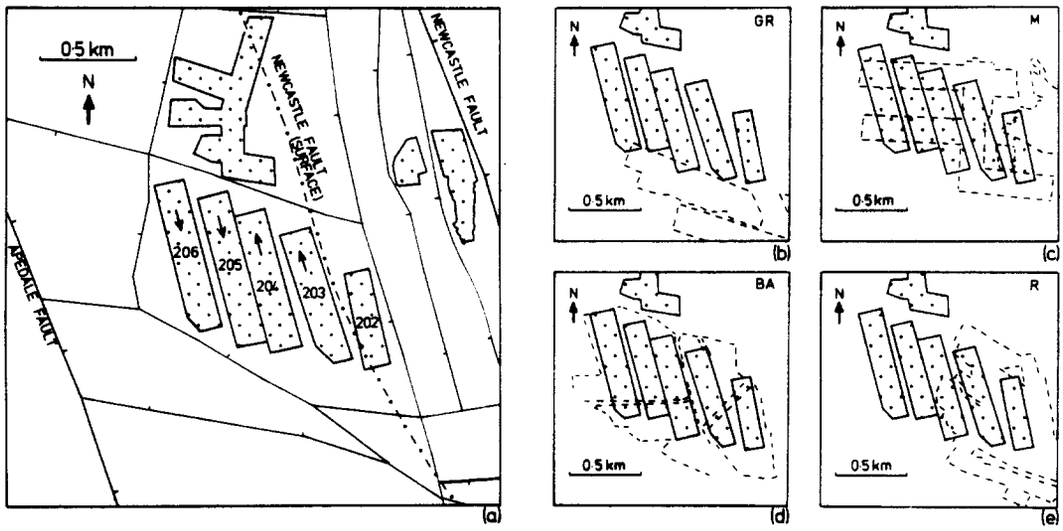

Fig. 1. The location of the Ten Feet seam mine workings (dotted ornament) including panels 202–206 together with (a) faults at the datum of the Ten Feet panels. (b) previous mine workings in the Great Row seam (GR). (c) Moss seam (M). (d) Bowling Alley seam (BA). (e) Rowhurst seam (R).

it, and a wave of subsidence is initiated which goes right to the surface.

Quite commonly, more than one face may be in production at one time but in the period covered by this report, panels 204, 205 and 206 of the Ten Feet seam were worked consecutively. 204's was worked from south to north with access roads being driven at the face ends (advancing). 205's and 206's were worked from north to south on pre-driven acess roads (retreating). As can be seen from the plans of the workings, pillars of coal were left unworked between all of these faces except 204's and 205's. The area had previously been mined in several other seams (Fig. 1). Mining conditions for panels 205 and 206 were generally good. No rockbursts were reported to have occurred by underground workers. Some deterioration of the condition of the panel access roads did however occur when passing under or above the Moss and Bowling Alley pillars.

The geological sequence of the mined area consists of numerous coal seams occurring in a cyclical sequence with mudstone roofs and floors with occasional intervening sandstones. A geological section, parallel to the line of advance of panel 205 is shown in Fig. 2. The dip is to the south at about 8°. The position of the Ten Feet, Moss, Bowling Alley, Great Row and Rowhurst coal seams are also shown. The sandstones are generally thin and non-continuous forming lenticular shaped bodies. Figure 2 therefore shows a very generalized geological section and at any one place a particular sandstone may be absent. The area of interest lies between the Newcastle and Apedale faults. In addition to these large faults several other minor faults also exist (Fig. 1).

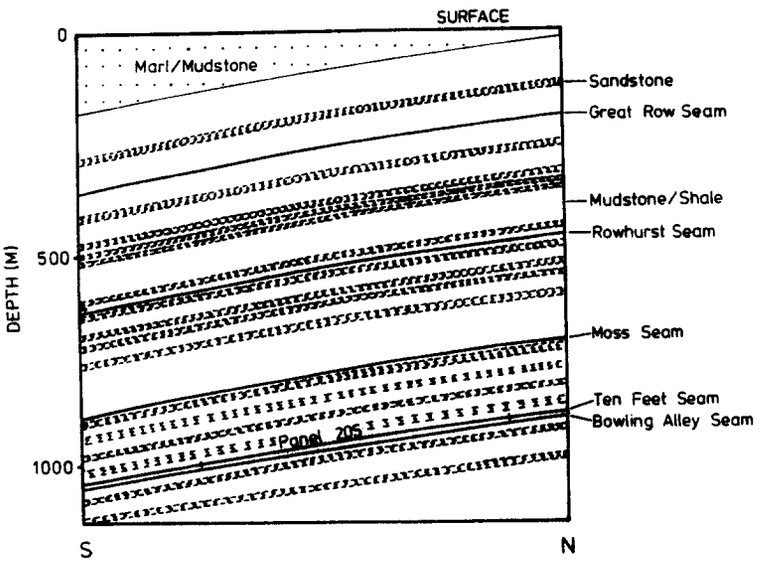

Fig. 2. Geological section along the line of panel 205 showing major sandstone units (shaded), the Ten Feet, Moss, Bowling Alley, Great Row and Rowhurst seams. Depths are from the surface.

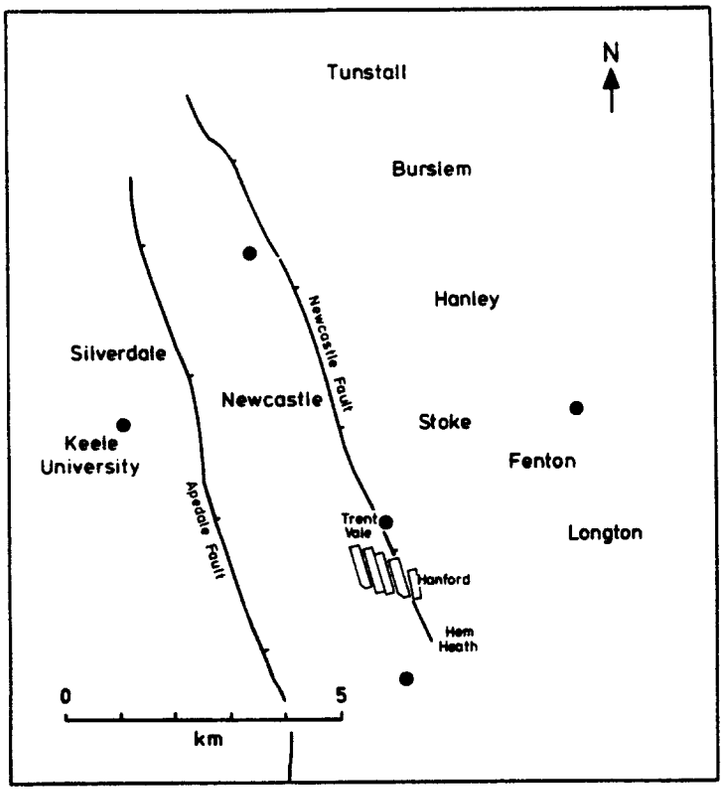

Fig. 3. Map showing location of network seismometers throughout the Potteries, and the Ten Feet seam panels. Seismometers are represented by solid circles.

In this paper the results of the analysis of earth tremors occurring during the working of panels 205 and 206 are described.

2. THE SEISMOMETER NETWORK AND ANALYSIS OF DATA

In order to determine the cause of the earth tremors and their generative mechanism a seismometer network was set up in and around Stoke-on-Trent to enable the hypocentres of the tremors to be found. The locations of the individual seismometers within the network are shown in Fig. 3. The geometry of the seismometer network was designed not only to monitor seismic activity in the immediate vicinity of the Ten Feet seam panels 205–206, but also over the whole of the Stoke-on-Trent conurbation. Seismometers were situated at the surface. Vertical component seismometers were used at all locations with the exception of the Keele site where 2 horizontal instruments detecting NS and EW components were also installed. The signal output of seismometers, proportional to the velocity of ground movement, was amplified, frequency modulated and transmitted by U.H.F. radio link to Keele University where the data was recorded on a Racal geostore 14 channel tape recorder. The seismometer network system employed has been described by Browitt [1]. The network was installed and operated in collaboration with the Global Seismology Unit of the Institute of Geological Science. The seismometer network recorded earth tremors from September 1975 to September 1977 during which panels 204, 205 and 206 were mined.

Data recorded on the tapes were played out to give a paper record which was examined for the occurrence of tremors. The hypocentre for each tremor was then calculated from the seismometer network seismograms, using the relative P wave arrival times at each seismometer. The seismic velocity structure used in the calculation of hypocentres has a linear increase in velocity with depth of 1.2 km/sec per km. This velocity structure was obtained from a calibration test shot and is preferred to a simple refractor velocity structure. The linear increase in velocity with depth was further substantiated by a borehole sonic log and from the velocity structure derived from joint hypocentral location techniques. The test shot also provided delay times for each seismometer station which were applied to the seismic arrival time data prior to hypocentre calculation. The computation of the tremor hypocentres from the arrival time data was achieved by an iterative method which compares the computed arrival times, for a typical hypocentre location, with the observed arrival times. Using non-linear optimization techniques the variance between observed and computed arrival times may be minimized so providing the hypocentre solutions. The hypocentre calculation procedure has also been explained by Westbrook [2].

The non-linear optimization procedure used in the location compution also provides an estimate of the location accuracy. Location solutions have a standard

deviation of approximately 250 m on average. The error of location is greater in depth than in the 2 horizontal co-ordinates because of the seismometer network geometry.

Local magnitude, M_L, has been calculated for each earth tremor. Our magnitude calculation procedure has been calibrated using Institute of Geological Sciences Lownet seismometer network estimates for some of the larger earth tremors. The error in M_L is estimated to be ± 0.5. Urban noise has imposed a hypocentre location threshold of approximately $M_L = 1.0$ on the seismometer network.

3. THE SPATIAL DISTRIBUTION OF TREMOR HYPOCENTRES WITH RESPECT TO MINING ACTIVITY AND GEOLOGY

Results of the analysis of the recordings of earth tremors occurring during the mining of panels 205's and 206's are presented here. The spatial distribution of tremor hypocentres with respect to the mine workings and geology are shown in Fig. 4. Figure 4(a) gives a plan view while Fig. 4(b) and 4(c) show vertical sections perpendicular and parallel to the coal face. Tremors are represented by circles whose radius is proportional to the local magnitude, M_L. The tremors can be seen to cluster adjacent to the area of present mining activity and lie predominantly between the depths of 400 and 1000 m. Plan views of tremor hypocentres show that tremors occurring during the mining of a panel are not situated immediately above or below that panel but are displaced slightly to the east of that panel. This displacement of tremor hypocentres to the east of the active panel may be caused by a systematic location error, or it may be a real effect. The tremors do not cluster in the vicinity of the Newcastle Fault, nor apparently along any of the other known minor faults.

The relationship between the position of the tremor

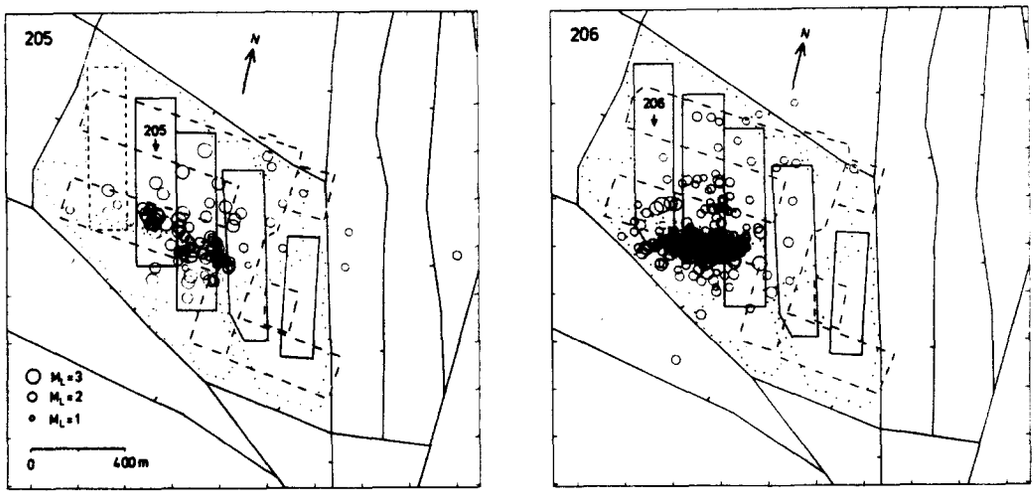

Fig. 4(a). Plan view of tremor hypocentres for tremors occurring during the mining of panels 205 and 206. Tremors are represented by a circle whose radius is proportional to the magnitude (M_L) of the tremor. Also shown are the location of the Ten Feet panels, Moss seam workings (dashed line) and Bowling Alley workings (dotted line). Faults are shown at the Ten Feet seam datum.

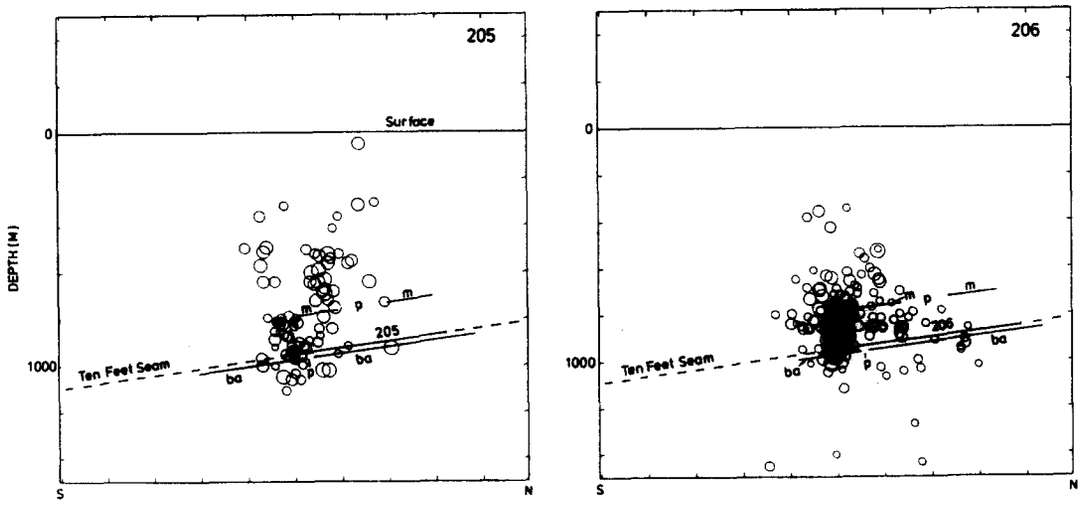

Fig. 4(b). Vertical section parallel to the line of advance of the coalface showing tremor hypocentres for panels 205 and 206. Previous workings in the Moss (M) and Bowling Alley seams (BA) are also shown together with pillars (P) in these workings.

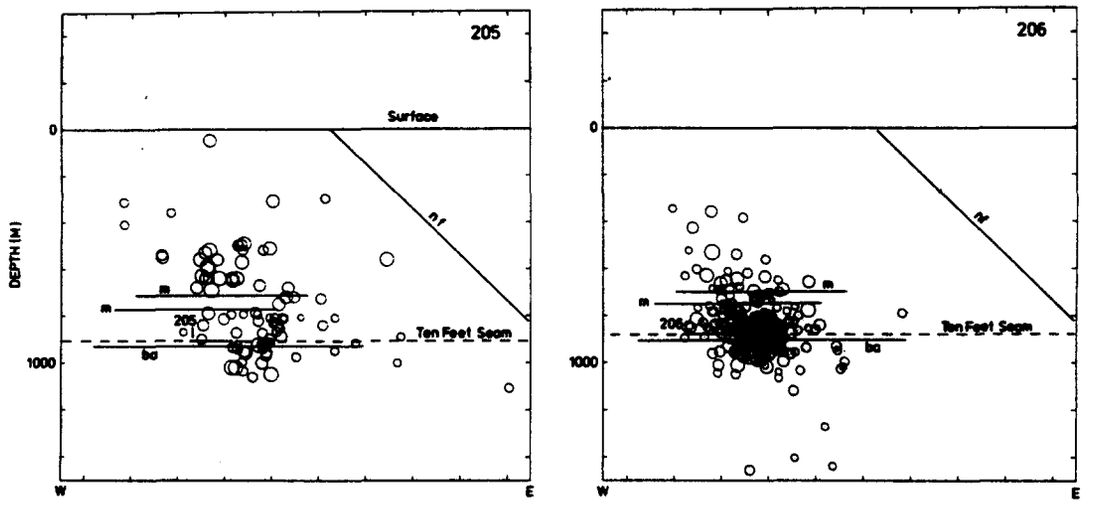

Fig. 4(c). Vertical section parallel to the coalface showing tremor hypocentres for panels 205 and 206. The Newcastle fault is also shown (n.f.).

epicentres and the position of the working face as it advanced down the panel is shown in Fig. 5, where the horizontal position of the tremor, projected onto the line of face advance and measured from the start of the panel, is plotted against the distance advanced by the face. The plot shows that the tremors advance with the face. The tremors appear to lie just in front of the advancing face (approximately 100 m), however, the location resolution is insufficient to confirm this. Tremor activity is small initially but as the face progresses the activity builds up. Little activity is observed until the face has advanced about 250 m. Also shown in Fig. 5 is the position of old workings in the Moss and Bowling Alley Seams. The occurrence of tremors felt by residents appears to correlate with the passage of the Ten Feet face under and above pillars of the old workings in the Moss and Bowling Alley seams.

Figure 6 shows a plot of the depth of tremors against

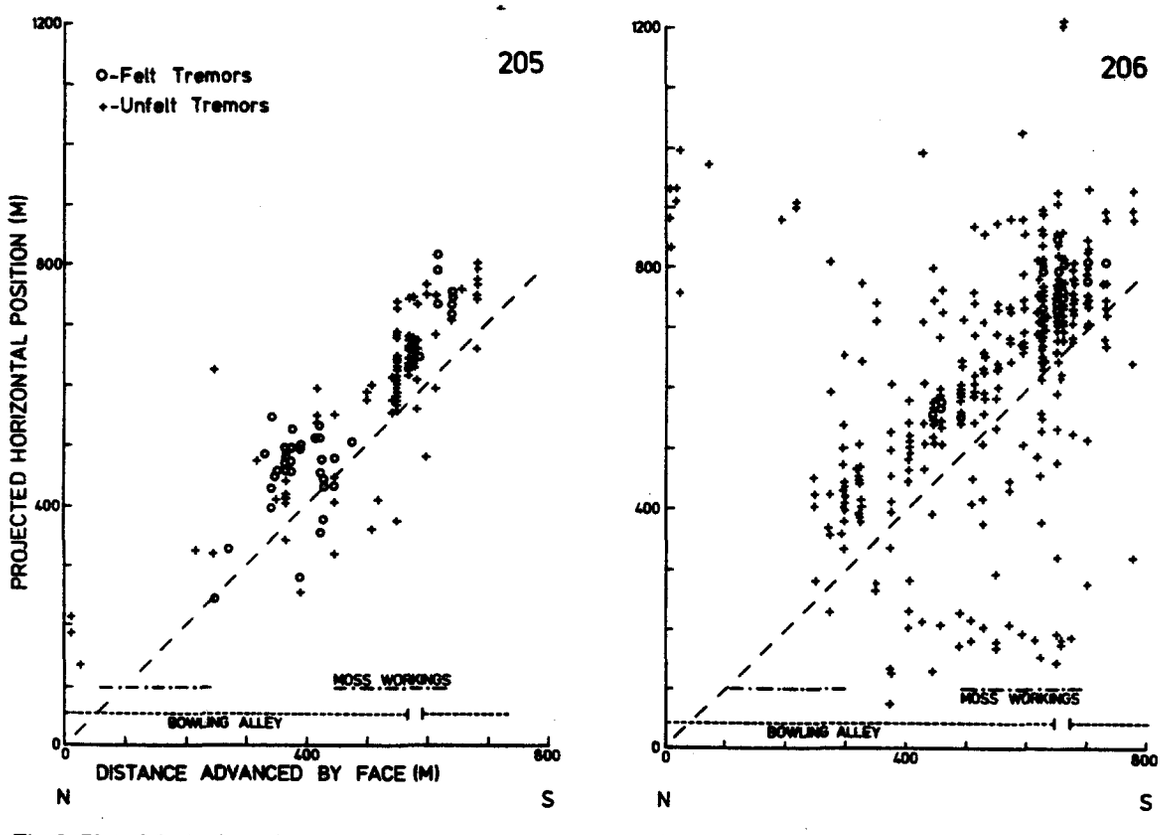

Fig. 5. Plot of the horizontal position of tremor hypocentres projected onto the line of face advance and measured from the start of the panel, against distance advanced by the face for tremors occurring during the mining of panels 205 and 206. The diagonal dashed line corresponds to the line on which tremors would plot if they occurred on the Ten Feet face. The region where the Ten Feet face lies above or below previous Moss or Bowling Alley seam workings is also shown.

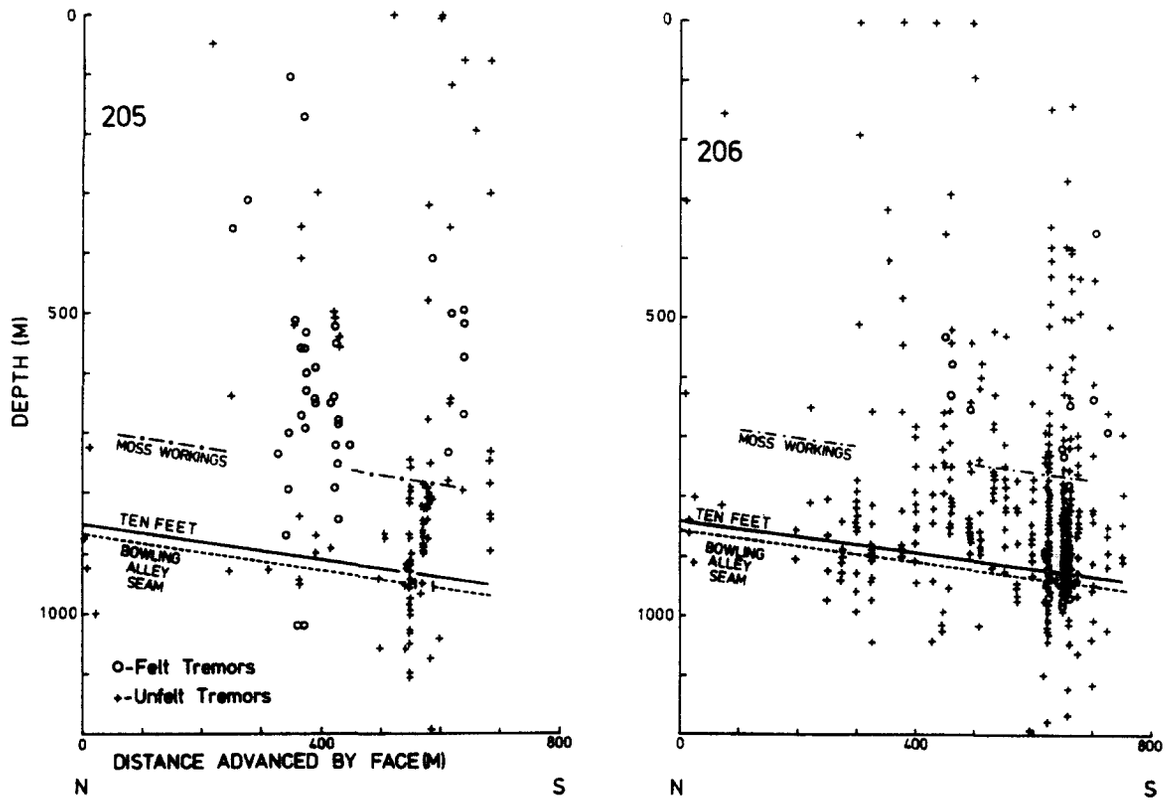

Fig. 6. Plot of tremor depth against distance advanced by panel for tremors occurring during the mining of panels 205 and 206. The position of Ten Feet seam working and previous workings in Moss and Bowling Alley seams are also shown.

the position of the advancing face. The correlation between the passage of the Ten Feet face under or over Moss or Bowling Alley pillars and the occurrence of felt tremors is again evident in Fig. 6. With the exception of those felt tremors associated with the Bowling Alley pillar, the felt tremors lie at a slightly higher level (approximately 650 m in depth on average) than the smaller unfelt events (850 m depth on average) although there is much scatter and overlap for each group. The depth range in the mined area of the Moss seam workings is approximately 700–800 m and that of the Ten Feet seam 850–950 m. Thus the smaller unfelt events appear to be located just above the level of the Ten Feet seam while the larger felt events are situated higher, at and above the level of the Moss seam, although the hypocentre location errors are such that we cannot be certain of this. The origin of the felt events some distance from the Ten Feet face is consistent with the fact that no tremors were felt by underground face workers. Most felt tremors occur when the Ten Feet face passes under Moss pillar. Felt tremors associated with the passage of the Ten Feet face over the Bowling Alley pillar only occur for panel 206. These tremors lie in depth at the level of the Bowling Alley pillar. A large increase in the number of unfelt tremors occurring is associated with the passage of the Ten Feet face above the pillar of the Bowling Alley.

The relationship between the depth and the local magnitude, M_L of a tremor is shown in Fig. 7. Those tremors felt by local residents are distinguished from those not felt. Felt tremors are, as expected, those of larger magnitude within the data set. The plot illustrates the intuitively obvious relationship that a tremor of a given magnitude is more likely to be felt if it is nearer the surface.

4. THE TEMPORAL DISTRIBUTION OF TREMORS

The histograms of Figs 8 and 9 show for both panels the daily and weekly temporal distribution of tremors occurring during the mining of those panels. Figure 8(a) shows the total number of tremors occurring on each day of the week, 8(b) the total number of tremors felt by local residents and 8(c) the total seismic energy released per day of the week. Seismic Energy, E, has been calculated using the relationship [3] given below,

$$\text{Log E} = 9.9 + 1.9\,M_L - 0.024\,M_L^2$$

The histogram for both panels shows a strong relationship between mining activity, which was largely restricted to Monday to Friday and the occurrence of tremors. The histograms for felt tremors and energy strongly display this relationship.

The variation of tremor activity with time during the mining of panels 205 and 206 is shown in Fig. 9 by dividing the time period, in which the panels were worked, into week long time units. The histograms show the number of tremors occurring per week, Fig. 9(a), the number of tremors felt by local residents,

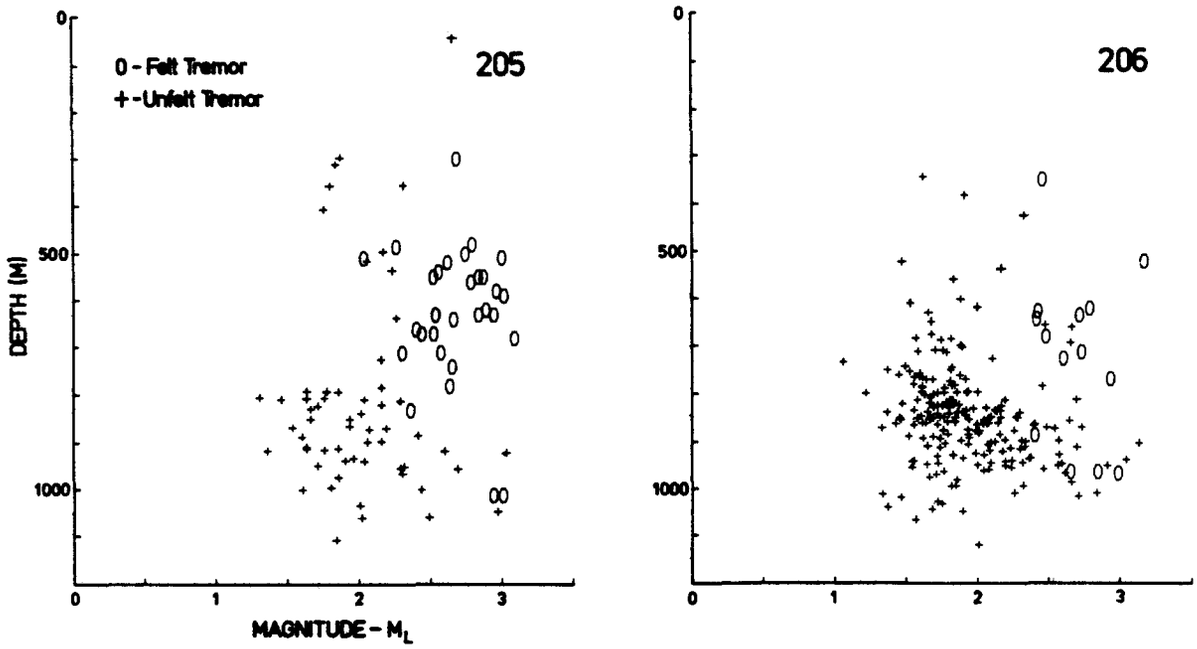

Fig. 7. Plot of depth of tremor against local magnitude, M_L, for tremors occurring during the mining of panels 205 and 206. Felt and unfelt tremors are distinguished.

9(b), and the total seismic energy, 9(c). Tremor activity is noticeably greater during the later half of the lives of both panels. The histogram showing the total number of tremors occurring per week is perhaps a poor guide to seismic activity since both large and small tremors are given equal weighting. The histograms showing felt tremors and energy are therefore a better guide to the level of seismic activity, since the larger tremors have greater weighting in their histograms. The time period during which the face passed under the old workings in the Moss and above Bowling Alley seams is also shown in Fig. 9. From the histograms for felt tremors and energy a correlation between the passage of the Ten Feet face under or above pillars and seismic activity

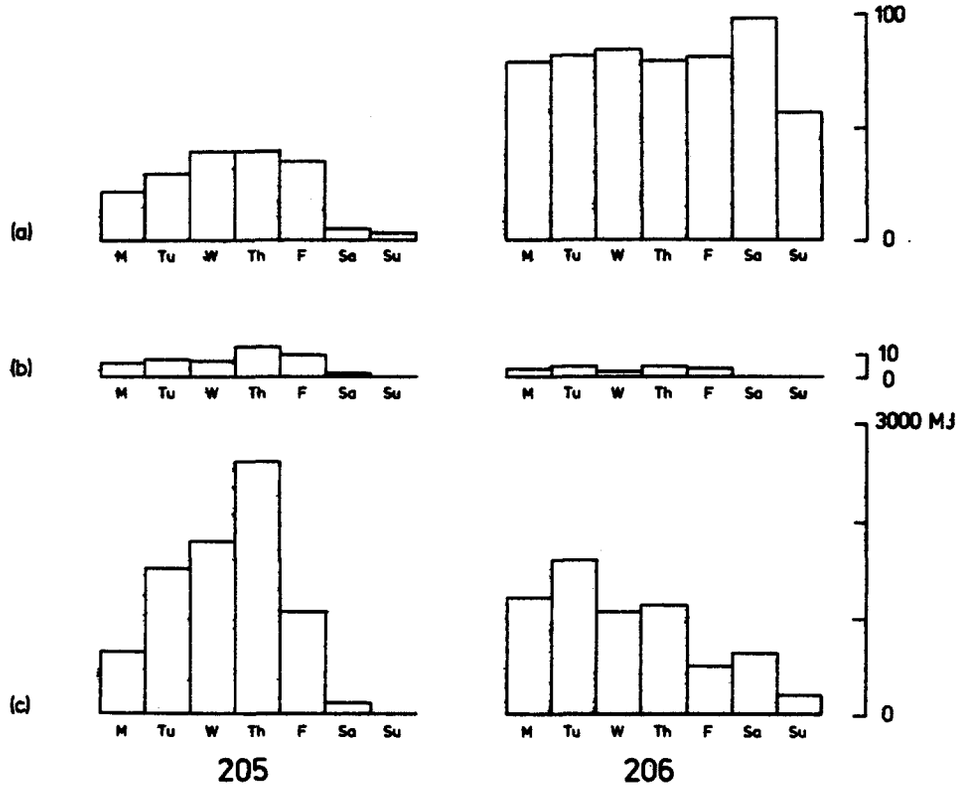

Fig. 8. Histograms of (a) total number of tremors per day of week, (b) number of felt tremors and (c) total seismic energy for panels 205 and 206.

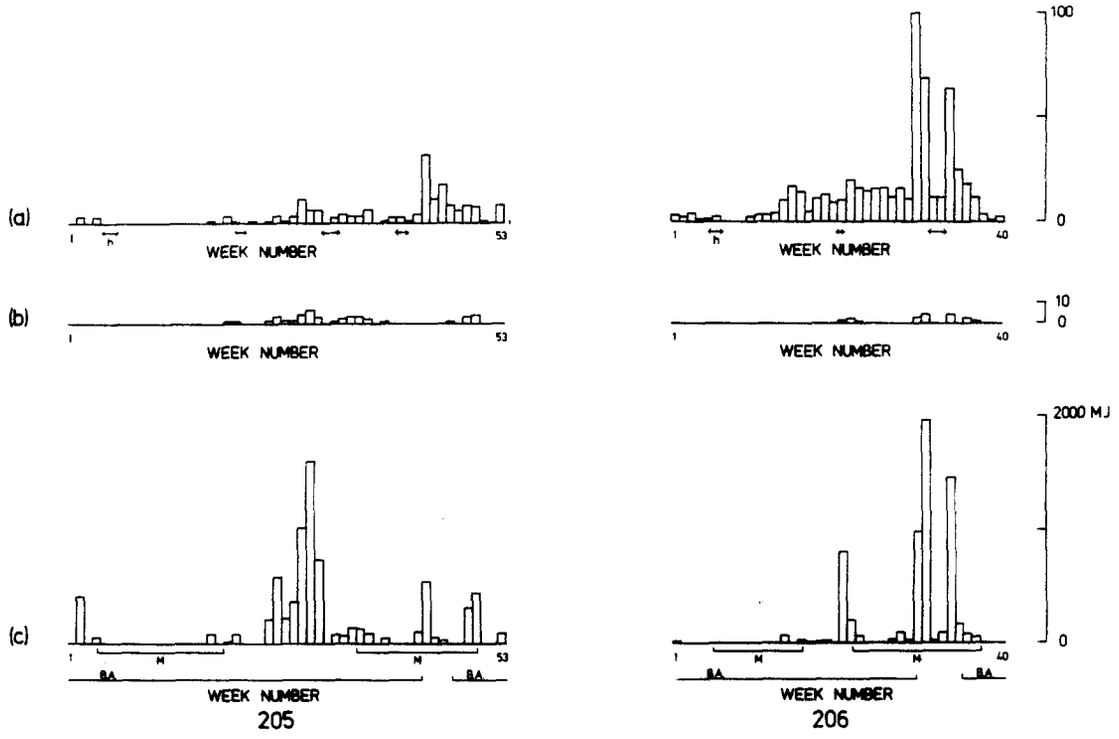

Fig. 9. Histograms of (a) total number of tremors per week, (b) number of felt tremors and (c) total seismic energy for panels 205 and 206. The periods during which the Ten Feet face was passing under previously extracted Moss seam (M) and Bowling Alley (BA) is shown. Periods of no mining activity (holidays) are also indicated (h).

can be seen. This correlation is more evident for panel 205 than 206. It is significant that some distinctive gaps in seismic activity correspond to periods of no mining during miners' holiday (see Fig. 9).

5. SPECULATIONS ON THE EARTH TREMOR GENERATION MECHANISM

While a causal relationship between coal mining and felt tremors is evident, further factors must be involved since mining is not normally accompanied by tremors. These further factors could include (a) geological faults and/or joints, (b) anomalous strata or geological structure, (c) previous mine workings, (d) a combination of some or all of the above factors. These possible contributing factors will be considered in turn.

(a) Faults could interact with mining to produce tremors in 2 possible ways. The mining process could trigger the release of natural stresses along the fault to produce the earth tremors, however this is unlikely because the area is not seismically active. Alternatively the fault could modify the distribution of stress around the mine workings in such a way that large stress concentrations arise so generating the earth tremors. Several faults are known in the mined area and enclose the 202–206 set of Ten Feet seam panels (Fig. 1). The hypocentres of tremors are located (Fig. 4) well to the west of the Newcastle fault and it is felt improbably that this fault has any direct influence on the occurrence of tremors. Furthermore, the earth tremors do not locate along any of the smaller faults within the area. The existence of minor faults and planes of weakness within the mined area cannot be overlooked and it is possible that sudden movement along these in response to the mining process could cause earth tremors. The direction of secondary cleat which is subparallel to 205's and 206's face may further contribute to the tremor mechanism.

(b) The existence of strata of high strength, such as thick sandstone beds, could result in a large amount of strain energy being stored within those strata during subsidence associated with the active face. Sudden release of the stored energy could result in large earth tremors. The vertical distribution of earth tremor hypocentres and the position of the sandstone beds are shown in Figs 4 and 2. The lack of resolution of the tremor hypocentre depth determination with respect to the thickness of the sandstone beds does not permit a meaningful comparison between tremor hypocentre position and the existence of a sandstone bed at that point. As mentioned previously in section 1 the sandstone bodies are generally thin, lenticular and non-continuous.

(c) Previous workings in other seams will have left their pillars in a residual overstressed state while the area above and below the old workings will be destressed. Mining in the Ten Feet seam will give rise to overstressing ahead of the face. At Trent Vale the old workings in the Moss and Bowling Alley seams are sufficiently close to the Ten Feet seam to allow the

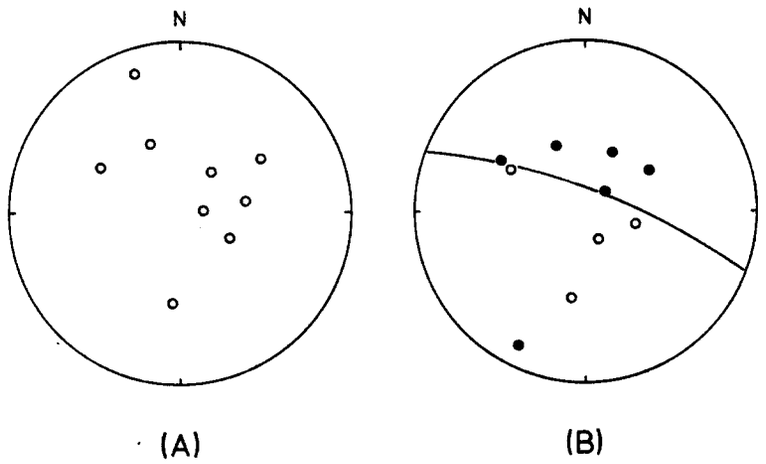

Fig. 10. Lower hemisphere stereographic projection plots of first motions for 2 earth tremors. Solid circles represent compressional first arrivals while open circles represent dilational first arrivals. Plot A shows a tremor with dilational first motions while Plot B shows a tremor with mixed compressional and dilational first motions. Plot A is interpreted as corresponding to a tremor with an implosional source mechanism, while plot B indicates a tremor with fault type or shear source mechanism. Only one of the 2 possible fault planes is identifiable in plot B.

overstressed regions around the two mining excavations to interact. The two zones of overstressing will coincide and compound as the Ten Feet face passes under or above the pillars of the old workings and consequently may give rise to a highly overstressed region giving extensive fracture and tremors.

The correlation of the occurrence of the large felt tremors with the passage of the Ten Feet face below and above the Moss seam and Bowling Alley seam pillars (see Figs 5 and 6) suggests that this mechanism may be responsible for the generation of the larger tremors. The smaller unfelt tremors however do not show this relationship except when the Ten Feet passes above the Bowling Alley pillar.

Analysis of the first motion directions of the seismic wave at each seismometer within the network suggests that 2 different mechanisms may generate tremors. First motion stereographic projections for 2 typical examples are shown in Fig. 10. The first motion analyses shown use additional seismic data collected on a temporary seismometer network situated above the active mine workings. Most small tremors give a first motion which is dilational at all seismometers indicating an implosional or collapse type mechanism. In contrast the larger tremors, including those felt by local inhabitants give first motions indicating a shear fracture type of source mechanism. Although it is not possible to determine unambiguously the orientation of the two possible fault planes for these shear events, there appears to exist over the whole data set a large number of different fault plane solutions, suggesting many different orientations of fracture planes.

The tremors may tentatively be classified into 2 groups.

Group one consists of smaller amplitude tremors, not felt by local residents and showing an implosional type of mechanism. While the occurrence of these tremors does not appear to be obviously influenced by the Moss pillar, the passage of the Ten Feet Face over the Bowling Alley pillar is associated with a large increase in the occurrence of this type of tremor.

Group two consists of larger amplitude tremors, usually felt by local residents and showing a shear fracture type of source mechanism. They occur when the Ten Feet seam face passes under or above the Moss or Bowling Alley pillars.

It is proposed that the *group two* tremors are caused by rock fracture within the Moss seam and Bowling Alley seam pillars when they are over-stressed by the advancing Ten Feet face. This felt tremor mechanism provides also an explanation of the seismicity felt in January, February and July of 1975 during the mining of panel 204, before the establishment of the seismic network. In January and February 1975, 204's Ten Feet face was passing over a narrow pillar in the underlying Bowling Alley while in July it was passing under a Moss pillar edge, alongside a narrow Bowling Alley pillar, under the corner of a panel in the overlying Rowhurst seam and was nearly abreast of the finishing line of the previous Ten Feet panel from which it was separated by a 40 m pillar. The implosional nature of the source mechanism of *group one* tremors together with the lack of a definite correlation between their occurrence and the position of the Ten Feet face with respect to pillars of previous workings and their smaller magnitude suggests that these tremors are caused by strata collapse and caving within the waste. The observation that many tremor hypocentres are situated to the east of the active panel (see Fig. 4) may indicate that the extraction of the currently active panel reactivates strata collapse and caving within the waste of the previous panel situated by its side.

The low level of seismic activity at the start of panels 205 and 206 and its build-up with the progress of the face, as shown in Figs 5 and 6 may suggest that the ground is weaker to the south. Alternatively and more likely the stress field, associated with the Ten Feet seam

panels, increases with increase in panel span tending asymptotically to a maximum. The critical span for the onset of the induced seismic activity appears to be of the order of 250 m.

DISCUSSION AND CONCLUSIONS

Induced seismicity associated with gold, coal and ore mining occurs in many parts of the world and this phenomenon has been investigated in detail in many cases including South Africa, Utah-U.S.A., Silesia-Poland, Canada and India [4–15]. In all of these cases a direct causal relationship between mining and seismicity has been established and the occurrence of earth tremors frequently coincides with underground reports of rock bursts. In this last feature the mining induced seismicity of North Staffordshire differs in that rock bursts are not an underground hazard and no underground reports of the occurrence of the seismic events have been made. While in the Silesian and Utah case histories the events may occur at considerable distances below and to the side of the active mine workings, the induced seismicity reported in this paper is generally situated in the immediate vicinity of, and predominantly above, the active mine workings; in common with many South African case histories [6]. Natural seismicity, tectonic stress and faults do not appear to be important in North Staffordshire, in contrast to the Silesian and Utah case histories [8,10,11]. Also unlike many other case histories, our earth tremors do not appear to coincide with shot blastings [4]. In common with some Silesian case histories [12], previous workings above the active mining appear to be an important factor in the generation of the larger tremors reported in this paper, especially when the advancing face comes within the influence of the pillars of previous workings.

Although mining induced seismicity is known to occur elsewhere, the remaining important question which needs to be answered is why mining of the Ten Feet seam in Trent Vale/Hanford generated large magnitude tremors felt by local residents while other mining in the area, where previous workings exist also, does not generate felt tremors. A study of the geology does not immediately suggest any reason why this might be so, the geological faults do not appear to be a contributing factor and the area is not naturally seismically active. Alternative possibilities may be that the strata properties increase the overstressing effect caused by interseam interaction or that the lenticular sandstone bodies within the strata, of which little is known, modify the stress field around the mine workings leading to large stress concentrations. These two possibilities require further examination.

The conclusion that the felt larger magnitude tremors were caused by overstressing due to interseam interaction between the Ten Feet face and old workings suggests that if the Ten Feet seam were worked in a virgin area, felt tremors would not be generated. If it is wished to work the Ten Feet panel in future in an area where other seams have previously been worked then it would be expedient to lay out the panels within the plan position of the nearest worked panel in the sequence in order to minimize the effects of interseam interaction. It can be seen from figures presented in the paper that no felt tremors were generated while the Ten Feet face was working under Moss goaf except when it was also passing over a narrow Bowling Alley pillar. The unfelt tremors of small amplitude are interpreted as being the inevitable noise or vibration generated by strata in the act of subsiding. They do not appear to constitute any sort of hazard and no measures need to be sought for their avoidance or elimination.

In conclusion the general points which may be drawn from the investigation are:

(1) Tremors were associated with the extraction of faces in the Ten Feet seam.

(2) Tremor hypocentres moved in unison with the advancing coal face.

(3) The tremors did not lie on either of the major faults bounding the area.

(4) The majority of tremors were not felt at the surface. Of 169 tremors monitored while panel 205 was working, 39 were felt. Of 540 tremors associated with the working of panel 206, 16 were felt. None have been felt underground.

(5) Felt tremors occurred as the Ten Feet faces pass under or above pillars in the Moss and Bowling Alley seams.

(6) The greatest concentration of tremors occurred as the Ten Feet faces passed over a pillar in the underlying Bowling Alley seam.

(7) The tremors did not start until the face had progressed about 250 m.

(8) The tremor hypocentres appear to be displaced about 200 m to the east of the active Ten Feet panel, i.e. over the previous face, however, this may possibly be attributable to hypocentre location error.

(9) The larger magnitude events which were felt show a shear type of source mechanism while the remaining smaller unfelt events have an implosional mechanism.

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